Chapter 4

Multiplexing and Multiple Access

4.1 Introduction

The huge increase of requests for communication services (e.g., telephone, mobile, Fax, message, TV, Telex, Internet, etc) becomes overestimates. The reason is due to the increase of communications resource. There are three basic ways to increase the throughput (i. e., total data rate) of a communications resource:

1- Either to increase the transmitter's effective isotropic radiated power (EIRP) or to reduce system losses so that the received E_b/N_o is increases.
2- Provide more channel bandwidth.
3- Make the allocation of the communications resource more efficient.

The third approach is the domain of communications multiple access. For satellite example, the problem is to efficiently allocate portions of the transponder's fixed communication resource, to a large number of users who seek to communicate digital information to each other at a variety of bit rates and duty cycles. The multiplexing or the allocation of the communications resource could follow one of the following:

- Frequency Division Multiplexing, FDM. In FDM an analog signals occupying non overlapping frequency bands are combined (added) together and a specific signal can be recovered from the composite signal simply by filtering. Frequency division multiple access, FDMA, is FDM applied to satellite repeaters. Guard bands between accesses allow for imperfect filter and oscillators. Neither clocking control nor coordination between accesses is required other than remaining "on frequency".

- Time Division Multiplexing, TDM. In TDM signals samples occupying non overlapping time slots are combined together and a specific signal can be recovered by restoring the signal

samples from a specific time slot with very precise timing. Time division multiple access, TDMA, is the sharing of a satellite repeater by several earth stations which transmit in bursts timed and interleaved so as not to overlap each other in the repeater.

- Code Division Multiplexing, CDM. In code division multiple access, CDMA, all users operate at the same nominal frequency and simultaneously use the entire repeater bandwidth. Therefore, unlike FDMA or TDMA, minimal dynamic (frequency or time) coordination is needed between various transmitters in the system.

- Space Division Multiplexing, SDM, or multiple beam frequency reuse. Spot beam antennas are used to separate radio signals by pointing in different directions. It allows for reuse of the same frequency band.

- Polarization Division Multiplexing, PDM. Orthogonal polarizations are used to separate signals, allowing for reuse of the same frequency band.

As a summary multiplexing and multiple access refer to the sharing of a fixed communications resource. However, with multiplexing, users' requirements or plans for communications resource sharing are fixed, or at most, slowly changing where the resource allocation is assigned a priori. On the other hand, multiple access usually involves the remote sharing of a resource, such as a satellite.

4.2 Frequency Division Multiplexing/Multiple Access

4.2.1 Frequency Division Multiplex Telephony

In the early days of telephony, a separate pair of wires was needed for each telephone trunk circuit. Trunk circuits interconnect inter-city switching centers so that the skies of all the major cities in the world grew dark with overhead wires as the demand for telephone service grew. A major development in the early 1900s, FDM made it possible to transmit several telephone signals simultaneously on a single wire, and thereby transformed the methods of telephone transmission.

Communications resource can be viewed as a frequency-time plane in Fig.4.1. In FDM or FDMA, each signal (channel) is assigned a specific frequency band whereas different signals are separated with guard bands to minimize interference. Fig.4.2, For example, indicates the multiplexing of three voice signals, extends from 0.3 to 3.4 kHz. The first channel is mixed with 12 kHz carrier to produce the lower side band (LSB) that extends from 8.6 to 11.7 kHz. The second and third channels are mixed with 16 and 20 kHz carriers to produce the lower side bands 12.6-15.7 kHz and 16.6-19.7 kHz respectively. Thus, the guard band between channels carrying signals is thus 0.9 kHz. On mixing the three signals the composite spectrum extends from 8.6 to 19.7 kHz. Such a composite signal is known as "***subgroup***".

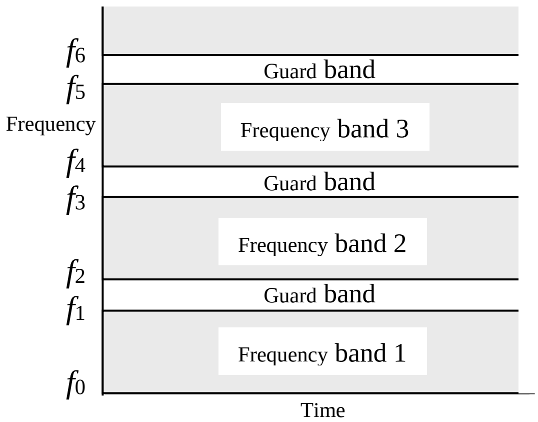


Fig.4.1 Frequency Division Multiplexing

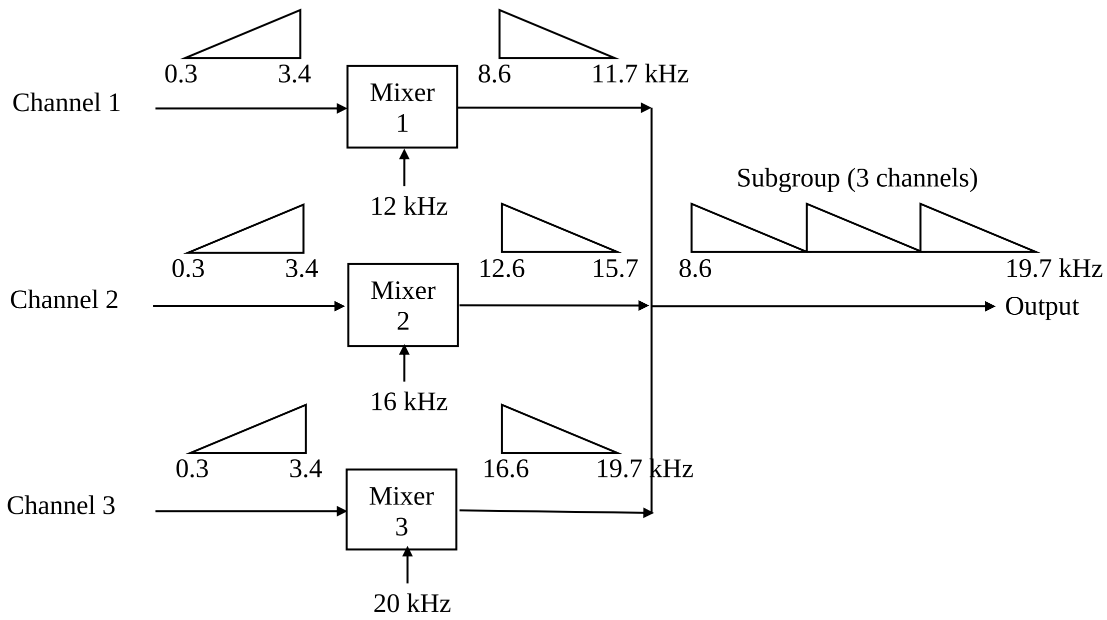


Fig.4.2 FDM Example to Produce One Subgroup Consists of 3 Channels

4.2.2 Frequency Division Multiplex Access for Satellite

Geostationary Satellite

Geostationary satellite means that the satellite is in a circular orbit, in the same plane as the earth's equatorial plane, and at such an altitude that the orbital period is identical with the earth's rotational period. Since such satellites appear stationary when viewed from the earth, three satellites spaced 120^{o} apart can provide worldwide coverage (except for polar regions). Therefore, most satellites are positioned in a geostationary orbit.

Nonregenerative Repeater or Transponder

Nonregenerative means that the uplink (earth-to-satellite) transmissions are simply amplified, frequency shifted, and retransmitted on the downlink (satellite-to-earth) without any demodulation/remodulation or signal processing.

C-Band

The most popular frequency band for commercial satellite communications, called C-band, uses a 6GHz carrier for the uplink and a 4GHz carrier for the downlink. Each satellite in C-band is permitted (by international agreement) to use a 500MHz. This wide band is typically divided to 12 transponders with a bandwidth of 36MHz each.

Modulation Plan of a Typical FDMA System (FDM/FM/FDMA)

The most common 36MHz transponder operates in an FDM/FM/FDMA (frequency-division, frequency-modulated, frequency-division multiple access) multi-destination mode. This means that:

"Composite FDM channels are FM modulated and transmitted to the satellite within the bandwidth allocation of an FDMA plan".

• FDM: As shown in Fig.4.3, a 12 voice channels, each one having about 4kHz SSB spectrum (including guard band) are FDM'd to form one group extends from 60-to-108kHz. Then 5 of these groups are FDM'd again to form one super group (60 voice channels; 5x12) extends from 312-to-552 kHz. The composite signal may be only one super group carrying 60 voice channel. Otherwise more and more FDM takes place to have more voice channels.
• FM: The composite signal (e.g., super group) is frequency modulated onto a carrier and transmitted to the satellite as one access.
• FDMA: The satellite receives many composite signals from different access positions (earth stations). Therefore, subdivision of the 36MHz transponder bandwidth may be assigned to different earth stations (users). Each earth station (user) receives a specific bandwidth allocation whereby it can access the transponder.

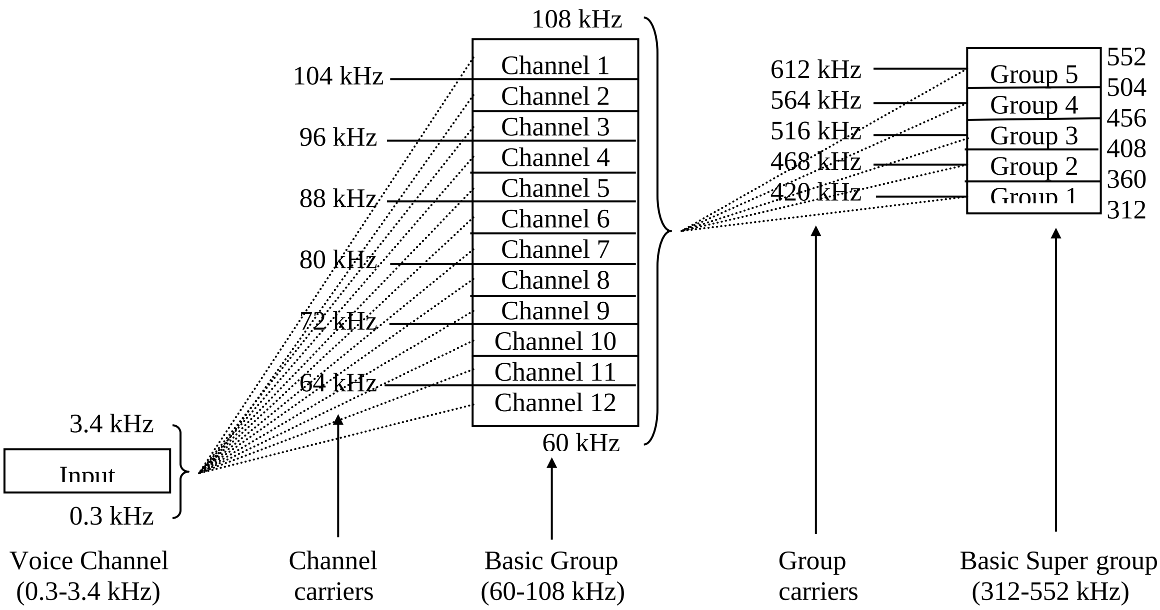


Fig.4.3 Modulation Plan of FDMA Systems

FDMA Analog Applications

- FDMA is extensively used with frequency modulation as in television distribution and broadcasting.
- Two TV signals on separate carriers through the same RF channel are feasible in a 36MHz bandwidth.
- Multi-channel-per-carrier MCPC or FDM/FM/FDMA of voice signals. Typical systems have 24 or 60 voice channels per access
- Single-channel-per-carrier SCPC telephony using FM (FM/SCPC).

FDMA Digital Applications (Examples)

- FDM/PSK/FDMA for telephony: INTELSAT, TELESAT, Western Union, RCA Americom, and American Satellite Corporation (ASC).
- TDM/PSK/FDMA for time division multiplex of PCM voice and data: Western Union, RCA Americom, COMSAT, ESA, and SYMPHONIE.
- Experimental systems at 180Mbps of digital TV as wideband digital services.

4.3 Time Division Multiplexing/Multiple Access

In TDM, the communications resource is shared by assigning each of the M signals or users the entire spectral occupancy of the system for a short duration of time called a time slot. Guard times allow for some time uncertainty between signals in adjacent time slots, and thus reduce interference as in Fig.4.4. Fig.4.5 illustrates the configuration of TDMA for satellite application:

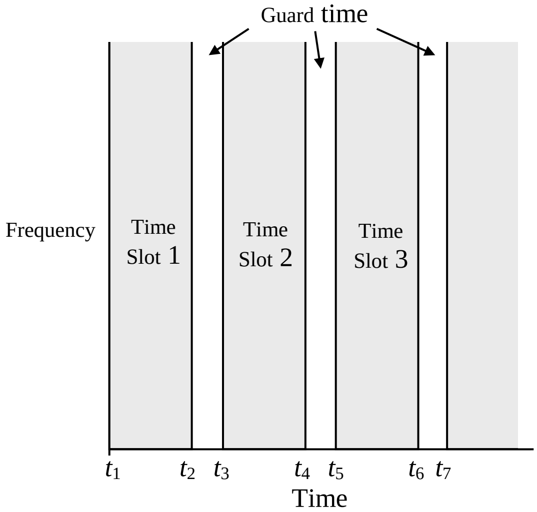


Fig.4.4 Time Division Multiplexing

- Time is segmented into frame intervals.
- Each frame is a further partitioned into assignable users time slots.
- The frame structure repeats, so that a fixed assignment constitutes one or more slots that periodically appear during each frame time.
- Each earth station transmits its data in bursts, timed so as to arrive at the satellite coincident with its designated time slot(s).
- When the bursts are received by the satellite transponder, they are retransmitted on the downlink, together with the bursts from other stations.
- A receiving station detects and demultiplexes the appropriate bursts and feeds the information to the intended user.

Fixed Assignment TDM/TDMA

The simplest TDM/TDMA is the fixed assignment scheme in which the *M* time slots that make up each frame are pre-assigned to signal sources, long term. The multiplexing operation consists of providing each source with an opportunity to occupy one or more slots. The demultiplexing operation consists of deslotting the information and delivering the data to the intended destination. In TDMA, the message itself is generally consists of a preamble portion and data portion. The preamble portion usually contains synchronization, addressing and error control sequences.

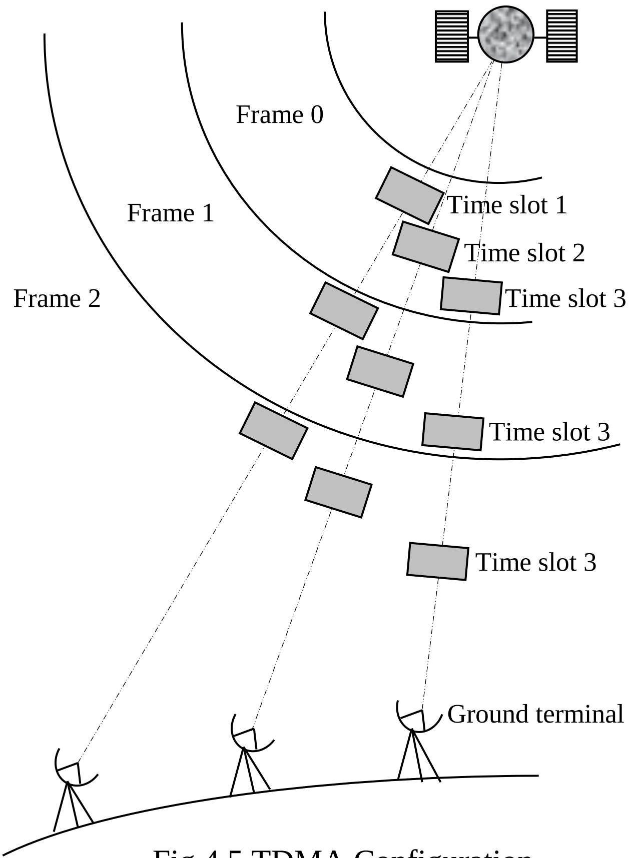


Fig.4.5 TDMA Configuration

A fixed assignment is efficient if the source requirements are predictable, and the traffic is heavy. However, for bursty or sporadic traffic, it is wasteful. When requirement are unpredictable, the dynamic assignment of slots can be more efficient. Such schemes are known as packet-switched systems, statistical multiplexers, or concentrators; in order to use all the slots in a frame in such a way that capacity is conserved.

4.4 Code Division Multiple Access

In code division multiple access CDMA of Fig.4.6 the communications resource is shared by slicing it horizontally to form FDMA frequency bands and vertically to form TDMA time slots. During time slot 1, signal 1 occupies band 1, signal 2 occupies band 2, and signal 3 occupies band 3. During time slot 2, signal 1 hops to band 3, signal 2 hops to band 1, and signal 3 hops to band 2, and so on. Code division multiple access CDMA is the hybrid combination of FDMA and TDMA. CDMA is an application of the spread spectrum techniques that are basically classified as follows:

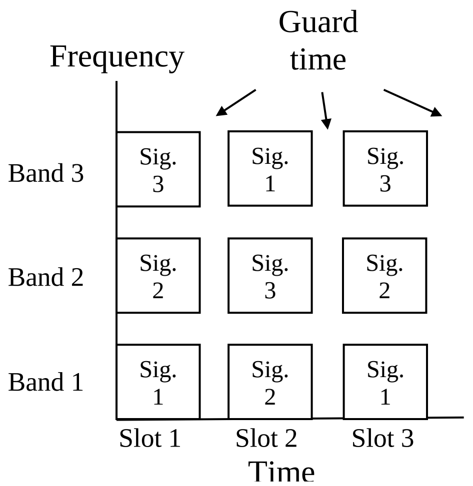


Fig.4.6 Code Division Multiplexing

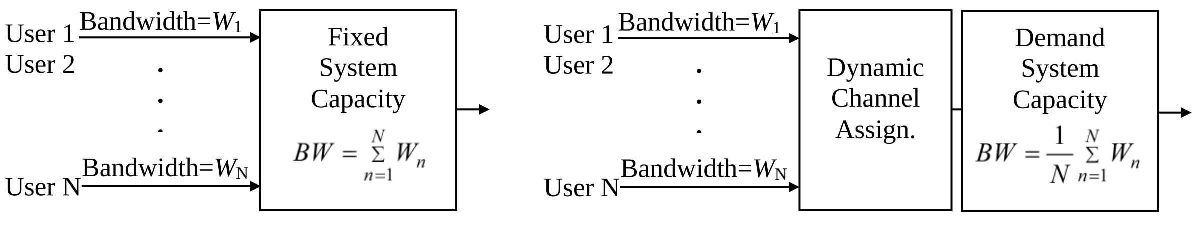
- Direct sequence spread spectrum
- Frequency hopping spread spectrum

CDMA offers some unique advantages over FDMA and TDMA as follows:

1- Privacy: The transmissions cannot easily be intercepted by unauthorized users without the code.
2- Fading degradation is shared among all the users: Fading randomly affects portions of the frequency range (by attenuation). In FH-CDMA scheme, only during the time a user hops into the affected portion of the spectrum, will the user experience degradation.
3- Jam resistance.
4- Flexibility: The most important feature of CDMA compared with TDMA is that there need be no precise time coordination among the various simultaneous transmitters (synchronization is only required between a transmitter and a receiver within a group).

4.5 Demand-Assignment Multiple Access (DAMA)

Multiple access schemes are termed fixed-assignment when a station has periodic access to the channel independent of its actual need. Dynamic or demand-assignment multiple access (DAMA) schemes give the station access to the channel only when it requests access. If the traffic tends to be burst-like, demand-assignment procedures can be much more efficient than fixed-assignment. By using buffers and DAMA, a system with reduced average capacity can handle bursty traffic, at the cost of some queuing delay. Fig.4.7 summarizes the difference between a fixed system, whose capacity is equal to the sum of the user requirements, and a dynamic system, whose capacity is equal to the average of the user requirements.



(a) Fixed assignment system (b) Demand assignment system

Fig.3.7 Bandwidth reduction for System Using Dynamic Assignment

4.5.1 Multiple Access Protocols (Algorithms)

A multiple access protocol is the rule by which a user knows how to use time, frequency, and code functions to communicate through a satellite to other users. The general goal of a multiple access system is to provide communications service in a timely, orderly, and efficient way. Fig.4.8 illustrates three different architectures for multiple access systems.

- In Fig.4.8.a, one earth station is designated as the master (the controller). This station possesses a multiple access computer program responds to the service requests of all other users. A user's request entails a transmission through the satellite and back down to the controller. The controller's response entails another transmission through the satellite. So, there are two up- and downlink transmissions for each service assignment.
- Fig.4.8.b illustrates the case the control is distributed among all the earth stations. Each station use the same algorithm and have identical knowledge regarding access requests and assignments. Therefore, only one round trip is required for each service assignment.
- When satellite is the controller, Fig.4.8.c, a service request goes from user to satellite, and the response from the satellite can follow immediately; so one round trip is required.

3.5.2 Demand Assignment Multiple Access Operation

Fig.4.9 describes the flow of information between the multiple access controller and an earth station sequentially as follows:

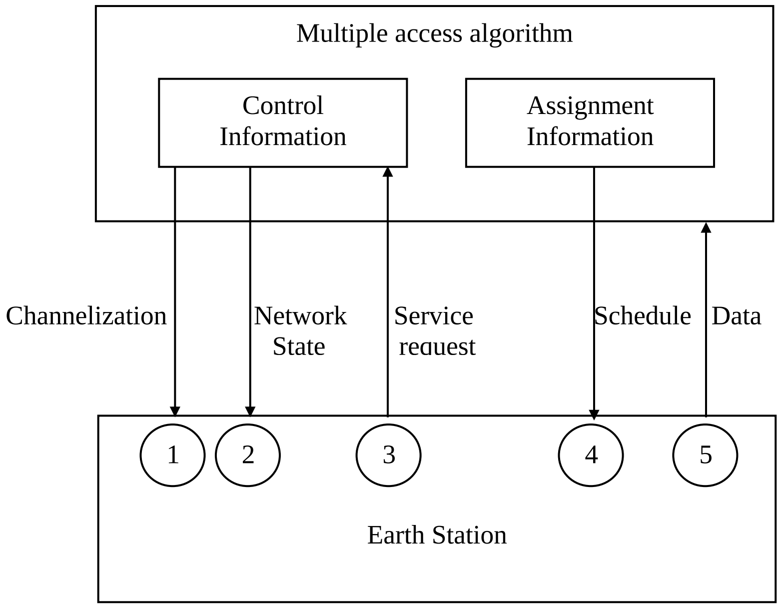


Fig.4.8 Access Architecture

Fig.4.9 Demand Assignment Information Flow

- Channelization: Allocation of channels 1 to N for Army and N+1 for the Navy, etc.
- Network state: A station is advised regarding the availability of the communications resource and where in the source (e.g., time, frequency, code position) to transmit its service request(s).
- Service request: The station makes its request(s) for service.
- Schedule: The controller sends the station a schedule regarding where and when to position its data.
- The station transmits its data.

4.6 Access Algorithms

4.6.1 Pure ALOHA Scheme

In 1971, the university of Hawaii began operation of its ALOHA system where a communication satellite was used to interconnect the several university computers by use of a random access protocol. The system simple concept includes the following modes:

- Transmission mode: Users transmit at any time they desire, encoding their transmissions with an error detection code.
- Listening mode: After a message transmission, a user listens for an acknowledgment (ACK) from the receiver. However, if the message collides (due to time overlap) with the messages from other users, a negative acknowledgment is received (NAK).
- Retransmission mode: When a NAK is received, the message are simply retransmitted after a random time.
- Timeout mode: IF, after a retransmission, the user does not receive either an ACK or NAK within a specified time, the user retransmits the message.

Message Arrival Statistics

Assume the average message or packet rate is denoted as λ. Because of the presence of collision, the total traffic arrival rate λ_t equals the acceptance rate λ plus the rejection rate λ_r:

$$\lambda_t = \lambda + \lambda_r \tag{4.1}$$

Assume the average length of packet is b bits. So, the average amount of successful traffic (throughput) and the total traffic are respectively expressed as:

$$\rho = b\lambda \quad \& \quad G = b\lambda_t \tag{4.2}$$

Assume the channel capacity (maximum bit rate is given by R bps, the normalized throughput and the total traffic are given by:

$$\rho_n = \frac{b\lambda}{R} \quad \& \quad G_n = \frac{b\lambda_t}{R} \tag{4.3}$$

Assume the transmission time of each packet τ is given by:

$$\tau = \frac{b}{R} \quad hence \quad \rho_n = \lambda\tau \quad \& \quad G_n = \lambda_t\tau \tag{4.4}$$

The arrival statistics is often modeled as a Poisson process. That is the probability of having K new messages arrive during a time interval τ sec is given by:

$$P(K) = \frac{(\lambda\tau)^K e^{-\lambda\tau}}{K!} \qquad , K \geq 0 \tag{4.5}$$

If another user began a message within the previous τ sec, its tail end will collide with the current message. If another user begins a message within the next τ sec, it will collide with the

tail end of the current message. So, for no collision, a space of 2τ is needed for each message. Thus, the probability P_s that a user message is successful (with no collision) is equal to the probability that 0 messages (K=0) are transmitted during a time interval 2τ:

$$P_s = P(K=0) = \frac{(2\lambda_t\tau)^0 e^{-2\lambda_t\tau}}{0!} = e^{-2\lambda_t\tau} \tag{4.6}$$

Also, the probability P_s that a user message is successful is given by definition as:

$$p_s = \frac{\lambda}{\lambda_t} \tag{4.7}$$

From the above equations, then:

$$\begin{aligned} \lambda &= \lambda_t e^{-2\lambda_t\tau} \\ \rho_n &= \lambda\tau = \lambda_t\tau\, e^{-2\lambda_t\tau} = G\, e^{-2G} \end{aligned} \tag{4.8}$$

A plot of the throughput ρ_n of pure ALOHA is shown in Fig.4.10. As G_n increases ρ_n increases until a point is reached where further traffic increase creates a large collision rate to cause a reduction in the throughput. The maximum throughput is equal to 0.18 and occurs at G_n=0.5. So, for pure ALOHA, 18% of communications resource can be only utilized.

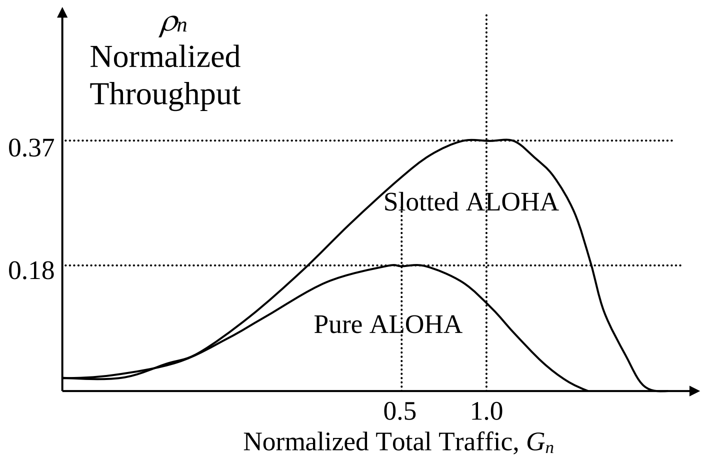


Fig.4.10 Throughput in ALOHA Systems

4.6.2 Slotted ALOHA

Pure ALOHA can be improved by making a small amount of coordination among the stations, which is the slotted ALOHA. A sequence of synchronization pulses is broadcast to all stations. Messages are required to be sent in the slot time between synchronization pulses, and can be started only at the beginning of a time slot. This reduces the rate of collisions by half, since only messages transmitted in the same slot can interfere with one another. The reduction in the collision window from 2τ to τ results in the following throughput:

$$\rho_n = G_n\, e^{-G} \tag{3.9}$$

Here, the maximum throughput is 0.37%. In slotted ALOHA, if a negative acknowledgment is received, the user retransmits after a random delay of an integer number of slot times as indicated in Fig.4.11.

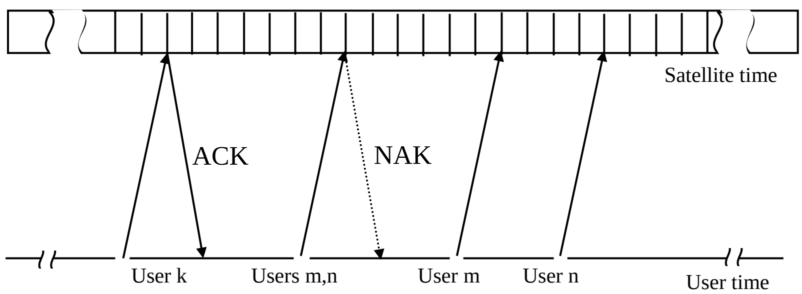


Fig.4.11 Slotted ALOHA Operation

4.6.3 Reservation ALOHA

A significant improvement was made to the ALOHA system with the introduction of reservation ALOHA scheme (R-ALOHA). It has two basic modes: an unreserved mode and a reserved mode as follows:

Unreserved Mode (Quiescent State)

When there are no reservations taking place, the system waits for requests of reservation:

1- A frame time is divided into a number of small reservation subslots.
2- Users use these small subslots to reserve message slots.
3- After requesting, the user listens for an acknowledgment and a slot assignment.

Reserved Mode

Once a reservation is made, the system is reconfigured as follows:

1- The time frame is divided into M+1 slots.
2- The first M slots are used for message transmissions.
3- The last slot is subdivided into subslots to be used for reservation/requests.
4- Users sent message packets only in their assigned portions of the M slots.

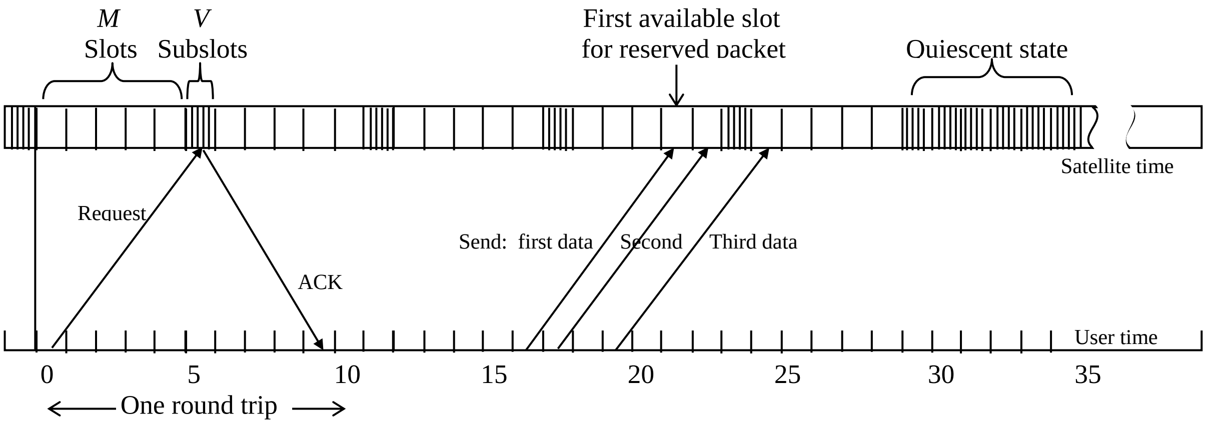


Fig.4.12 Example of Reservation ALOHA Operation

Fig.4.12 illustrates an example of reservation ALOHA, with 6 slots per frame, each can be divided into 6 subslots. In the quiescent state (no reservation) time is partitioned into short 6 x 6 = 36 subslots. Once a reservation is made, the system is reconfigured into M=5 message slots followed by V=6 subslots for reservation.

4.6.3 Comparison of S-ALOHA and R-ALOHA

Fig.4.13 compares the delay-throughput of S-ALOHA and R-ALOHA (with 2 message slots and 6 reservation subslots). At low values ρ<0.2, R-ALOHA pays the price of greater delay due to the greater overhead. For $\rho > 0.2$, collisions and retransmission of S-ALOHA cause a more quick delay increase. At higher throughput (ideal case 0.37 for S-ALOHA and 0.67 for R-ALOHA) the delay is unbounded.

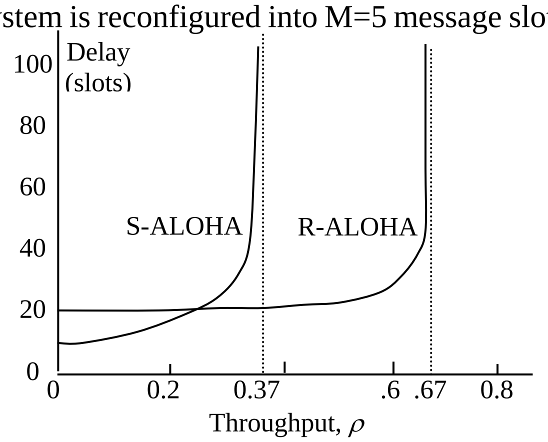


Fig.4.13 Delay-Throughput Comparison

4.7 Polling Techniques

That is to institute a controller that periodically pools the user population to determine their service request. One technique for rapidly polling a user population is called a binary tree search to resolve contention among users. A saving in time is possible for large population and small service demand. The number of decisions with a binary tree search for a population Q is:

$$n = \log_2 Q \tag{4.10}$$

Fig.4.14 illustrates a satellite example for 8 users population, with the identification 000, 001,… , till 111., and the following algorithm:

- Assume the terminals 001, 100, and 110 are contending for the service of a single channel.
- The satellite request the first bit of identification from the contending terminals.
- Terminal 001 transmits 0 and terminals 100 and 110 each transmit 1.The satellite selects 1 for example, on the basis of received signal strength S/N, and informs all terminals, so that half the user population knows that it has not been selected. So, terminal 001 bows out.
- The satellite requests the transmission of the second identifying bit from the remaining contending terminals.
- Terminal 100 transmits 0 and terminal 110 transmits 1. Assume the satellite selects 0; terminal 110 bows out so that terminal 100 is free to access satellite.
- When the channel becomes available, the above steps are repeated.

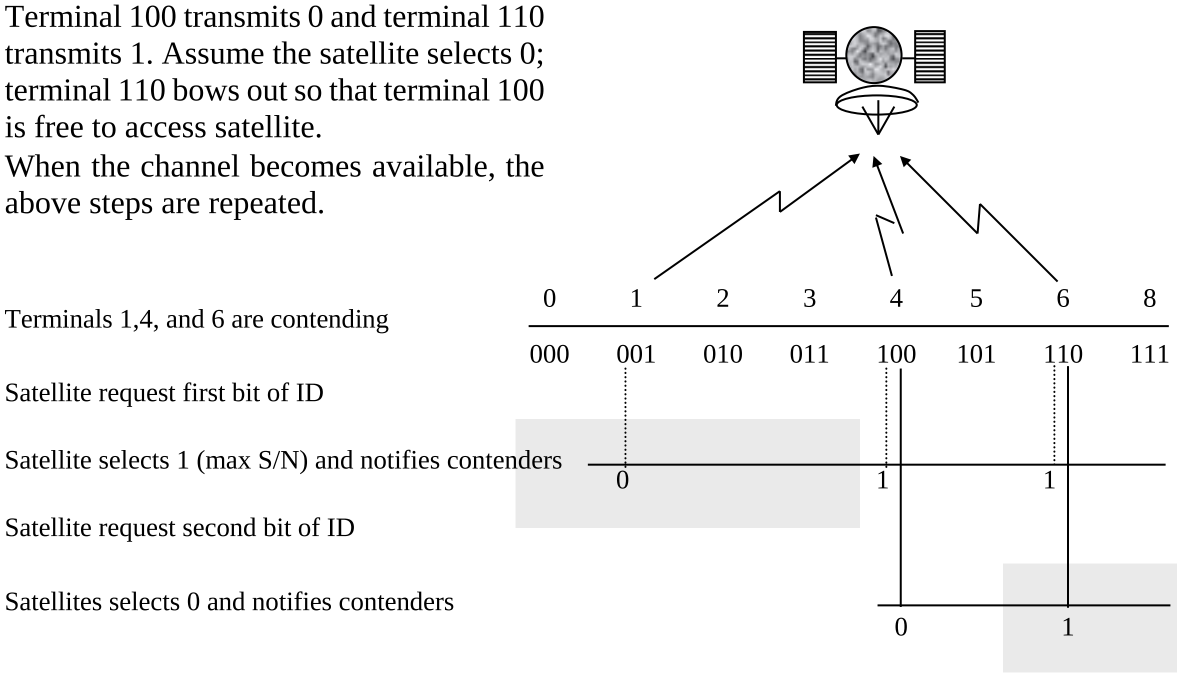


Fig.4.14 Binary Tree Search to Resolve Contention

Exercise 4.1: Calculate the time needed to provide channel availability to 100 terminals requesting service from a population 4096 terminals. Assume that the time required to poll one terminal and the time required for one decision of a binary tree search are each equal 1 sec.

Answer: **For straight polling** $T = 4096 x 1\sec = 4096\sec$

For binary tree search polling $T = \left(100 x \log_2 4096\right) x 1\sec = 1200\sec$